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## Charm at Threshold

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### Abstract

Results from the CLEO Collaboration, mainly dealing with the study of charmed mesons produced at flavor threshold but also covering other areas of CLEO's investigation, are reviewed.

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# 1 Introduction

The CLEO Collaboration at the Cornell Electron Storage Ring (CESR) studied  $e^+e^-$  collisions for nearly 30 years, taking its last data in March 2008. During this time it accumulated a wealth of data on charm and bottom quarks, some of which is still being analyzed. This report contains a selection of recent results.

In Sec. 2 we compare the properties of the CLEO III and CLEO-c detectors, and describe data samples and analyses in Sec. 3. An update of  $D^0$  and  $D^+$  branching fractions (Sec. 4) is in its final stages of analysis. Using the correlated nature of  $D^0$  mesons produced in  $e^+e^- \rightarrow \psi(3770) \rightarrow D^0\bar{D}^0$ , one can study CP- and flavor-tagged Dalitz plots for  $D^0$  decays (Sec. 5), which can help in the determination of the weak phase  $\gamma/\phi_3$  in  $B$  decays.

CLEO has recently performed an improved measurement of  $\mathcal{B}[\psi(2S) \rightarrow \pi^0 h_c]$  (Sec. 6) and searched for the transition  $\Upsilon(3S) \rightarrow \pi^0 h_b$  (Sec. 7). An unexpected result was the large production cross section for  $e^+e^- \rightarrow \pi^+\pi^-h_c$  at  $E_{\text{cm}} = 4170$  MeV (Sec. 8). Other recent CLEO results have been obtained for charmed particle final states with leptons (Sec. 9), including a search for  $D_s^+ \rightarrow \omega e^+ \nu_e$  (Sec. 10). Sec. 11 concludes.

## 2 CLEO III and CLEO-c detectors

Fig. 1 shows the latest incarnation of the CLEO detector, known as CLEO-c. It is the version used to study charmed meson production near threshold. It utilized an inner drift chamber, which replaced a silicon vertex detector in the CLEO III version in order to reduce multiple scattering. The CLEO III detector was used for the study of bottomonium and  $B$  meson pair production. Both versions of the detector had excellent neutral and charged particle energy/momentum resolution:  $\Delta E/E = (5\%, 2.2\%)$  at  $(0.1, 1)$  GeV for photons and  $\Delta p/p = 0.6\%$  at 1 GeV for charged tracks.

## 3 Data samples and analyses

We will not report today on the pioneering CLEO results above bottom pair production threshold, which include the first observation of the  $B^0 = \bar{b}d$  and  $B^+ = \bar{b}u$  mesons. Lower-energy samples discussed today are summarized in Table 1. Additional off-resonance samples were taken for continuum studies. The total number of CLEO publications as of April 2011 was 517, with three more under review. Approximately two dozen other analyses were still in progress. There have been 236 CLEO Ph. D. degrees, with an additional 32 devoted to the physics of the CESR storage ring and 14 more from the CUSB (Columbia University – Stony Brook) group whose detector operated on the other side of the ring from CLEO during the 1980s.

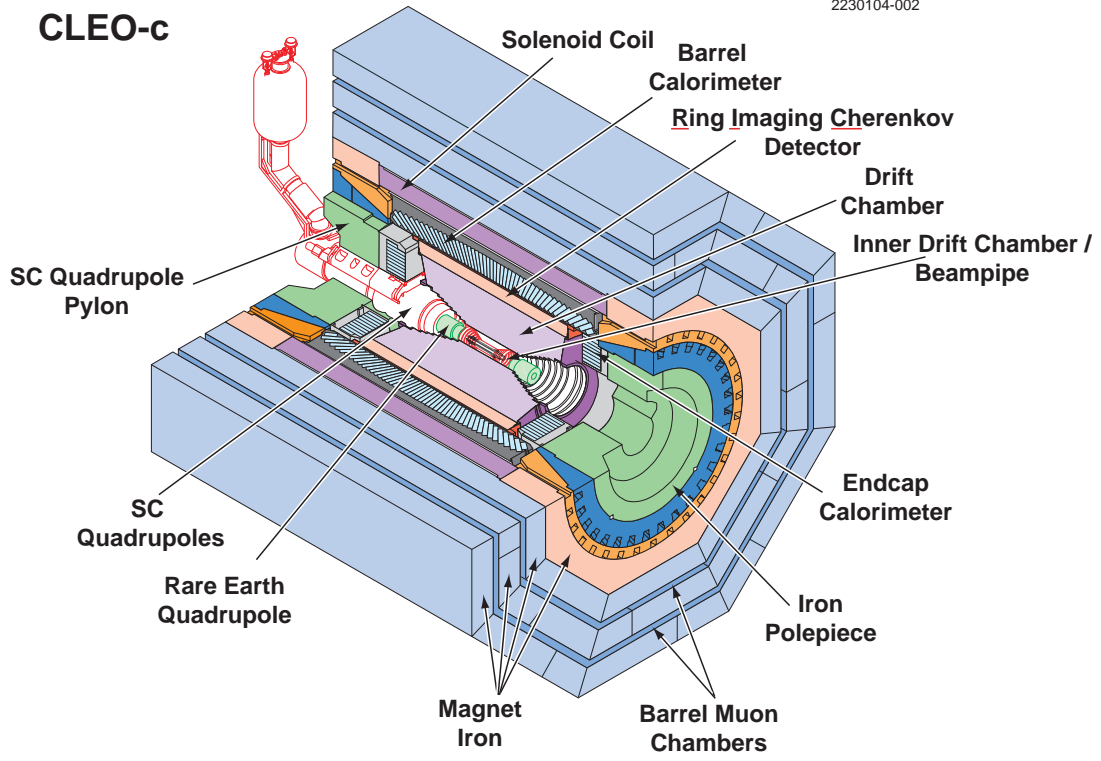


Figure 1: The CLEO-c detector

Table 1: CLEO data samples discussed in the present report.  $\psi(4170)$  denotes running at  $E_{\text{cm}} = 4170$  MeV; the accepted mass for the  $2^3D_1$  charmonium resonance is 4160 MeV/ $c^2$  [1].

	Initial state	Integrated luminosity (pb <sup>-1</sup> )	Decay products
Charmonium and charm	$\psi(3686)$	53.8	27 M total
	$\psi(3770)$	818	5.3 M $D\bar{D}$
	$\psi(4170)$	586	0.6 M $D_s^+ D_s^{*-} + \text{c.c.}$
Bottomonium	$\Upsilon(1S)$	1056	20.81 M total
	$\Upsilon(2S)$	1305	9.32 M total
	$\Upsilon(3S)$	1387	5.88 M total

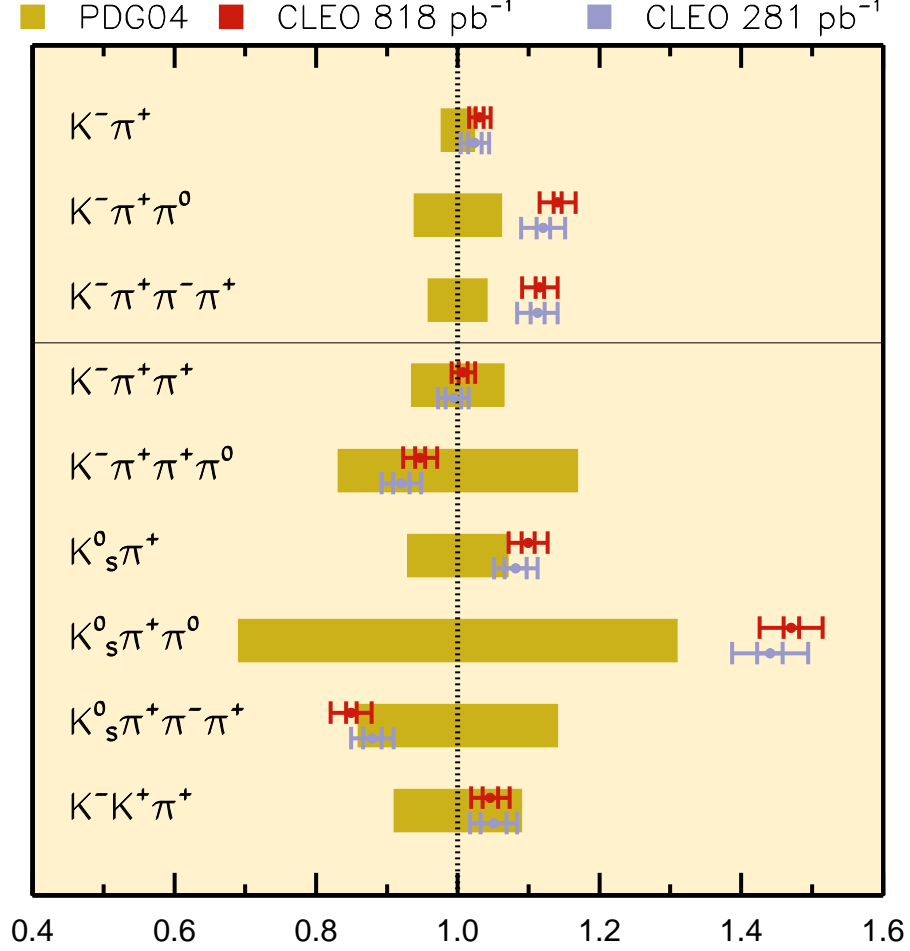


Figure 2: Ratios of branching fractions measured by CLEO with respect to 2004 compilation by Particle Data Group [2]. These results are preliminary.

#### 4 $D^0$ , $D^+$ absolute branching fractions

Preliminary branching fractions for a number of  $D^0$  and  $D^+$  final states based on the full sample of 818 pb<sup>-1</sup> [3] are compared in Fig. 2 with pre-CLEO-c Particle Data Group averages [2] and with published CLEO results based on 281 pb<sup>-1</sup> [4]. The analysis uses a combination of single-tag and double-tag methods. One outlying branching fraction is  $\mathcal{B}(D^+ \rightarrow K_S \pi^+ \pi^0)$ , found to be about 1.47 times the PDG 2004 value.

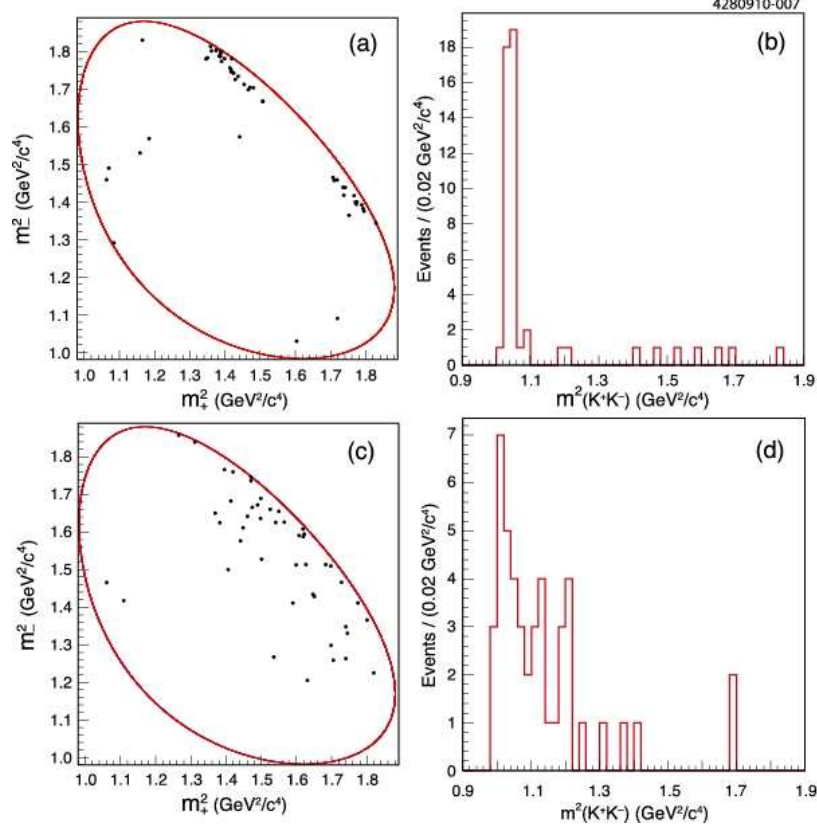


Figure 3: Dalitz plots for  $D \rightarrow K_S K^+ K^-$  and their  $K^+ K^-$  projections. Top: CP-even tag ( $\phi$  visible); bottom: CP-odd tag (no  $\phi$ ).

## 5 Tagged Dalitz plots; weak phase $\gamma$

The strong phase difference between  $D^0$  and  $\bar{D}^0$  decays to  $K_{S,L} h^+ h^-$  ( $h = \pi$  or  $K$ ) is important to learn the Cabibbo-Kobayashi-Maskawa (CKM) angle  $\gamma/\phi_3$  in  $B^- \rightarrow K^- D$  decays; the potential was seen of reducing the error  $\Delta\phi \simeq 9\text{--}10^\circ$  to a value of  $3\text{--}4^\circ$  using the current CLEO data [5] by exploiting the quantum coherence in  $\psi(3770) \rightarrow D^0 \bar{D}^0$ . This goal has in fact been achieved in a recent Belle analysis [6].

As an illustration of this coherence we compare Dalitz plots for  $D \rightarrow K_S K^+ K^-$  (Fig. 3) and  $D \rightarrow K_L K^+ K^-$  (Fig. 4) in which the companion  $D$  (the “tagging  $D$ ”) in  $\psi(3770)$  is CP-even (top panels) or CP-odd (bottom panels). The  $\psi(3770)$  decay produces a pair of  $D$  mesons in opposite-CP states, so a CP-even tag will lead to a CP-odd  $K_{S,L} K^+ K^-$  final state, and vice versa. This is borne out by the presence of a  $\phi$  in the  $K^+ K^-$  spectrum in the CP-even-tagged  $K_S K^+ K^-$  and CP-odd-tagged

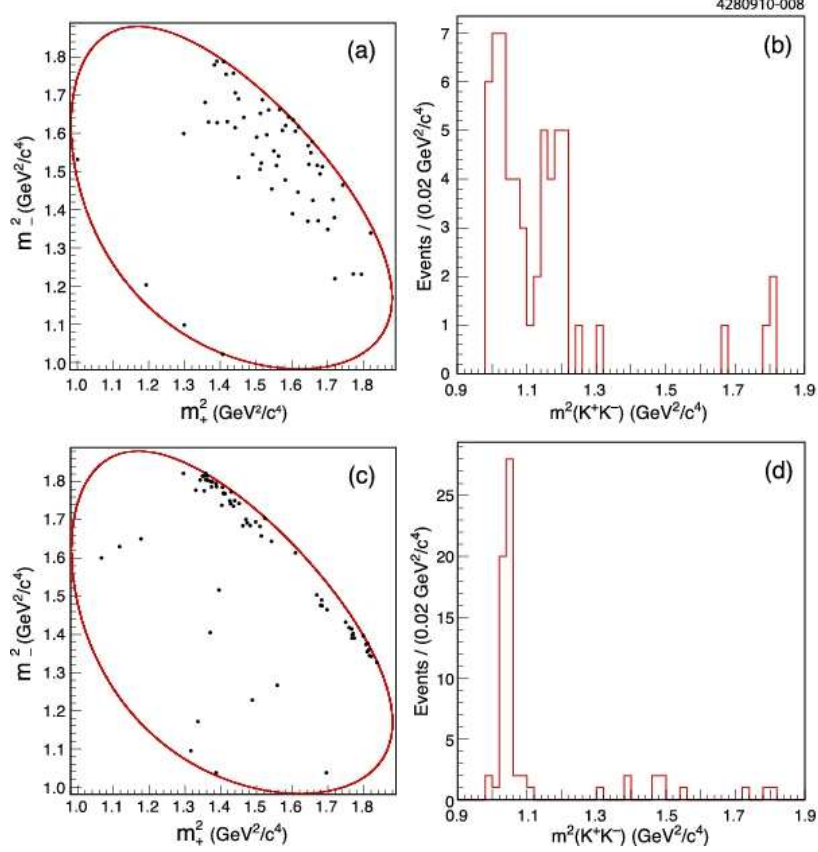


Figure 4: Dalitz plots for  $D \rightarrow K_L K^+ K^-$  and their  $K^+ K^-$  projections. Top: CP-even tag (no  $\phi$ ); bottom: CP-odd tag ( $\phi$  visible).

$K_L K^+ K^-$  final states, but not in the other two final states.

The use of  $D^0$  Dalitz plots in the study of  $B$  decays proceeds as follows [7]. The amplitudes  $\mathcal{A}(B^- \rightarrow D^0 K^-) \sim V_{cb} V_{us}^*$  and  $\mathcal{A}(B^- \rightarrow \bar{D}^0 K^-) \sim V_{ub} V_{cs}$  can interfere when they lead to the same final state  $f(D)$ . Their ratio is

$$\frac{\mathcal{A}(B^- \rightarrow \bar{D}^0 K^-)}{\mathcal{A}(B^- \rightarrow D^0 K^-)} = r_B e^{i(\delta_B - \gamma)}, \quad r_B \equiv \left| \frac{\mathcal{A}(B^- \rightarrow \bar{D}^0 K^-)}{\mathcal{A}(B^- \rightarrow D^0 K^-)} \right| \simeq 0.1. \quad (1)$$

where  $\delta_B$  is a strong phase difference. Atwood, Dunietz, and Soni [8] proposed the use of  $f(D) = K^+ \pi^-$ , while Atwood and Soni [9] suggested using multi-body  $D$  final states. In the latter case one has to determine a **coherence factor**  $R_F$  defined for the final state  $F$  ( $0 \leq R_F \leq 1$ ):

$$R_F e^{i\delta_D^F} = \frac{\int \mathcal{A}(s) \bar{\mathcal{A}}(s) e^{i\delta(s)} ds}{\sqrt{\int |\mathcal{A}(s)|^2 ds \int |\bar{\mathcal{A}}(s)|^2 ds}}. \quad (2)$$

Table 2: Coherence factors  $R_F$  for final states  $F$  in  $D^0$  decays.

$F$	$K\pi\pi^0$	$K3\pi$	$K_S K\pi$
$R_F$	$0.84 \pm 0.07$	$0.33^{+0.26}_{-0.23}$	$0.73 \pm 0.09$
$\delta_D^F$	$(227^{+14}_{-17})^\circ$	$(114^{+26}_{-23})^\circ$	$(8.2 \pm 15.2)^\circ$

Table 2 shows some coherence factors determined by CLEO [7]. One can reduce model-dependence by performing fits to Dalitz plots with bins of equal  $\Delta\delta_D^F$  [10, 11].

## 6 $\mathcal{B}[\psi(2S) \rightarrow \pi^0 h_c]$

We report here on a new CLEO result [12]. The numbers in this section and the next are preliminary. In the decay  $\psi(2S) \rightarrow \pi^0 h_c$  the  $\pi^0$  has an energy of 159 MeV. An important background from the photon in  $\psi(2S) \rightarrow \gamma\chi_{c2}$  pairing with a random low-energy photon can be suppressed by rejecting very asymmetric  $\pi^0$  decays. Fig. 5 shows the dependence on effective recoil mass against a  $\pi^0$  candidate of the energy of the higher-energy photon for various values of  $|\cos\alpha|$ , where  $\alpha$  is the angle of either photon in the  $\pi^0$  rest frame relative to the  $\pi^0$  boost direction. For values of  $|\cos\alpha|$  exceeding about 0.5, there is danger of confusion of the higher-energy photon in  $\pi^0$  with a photon from  $\psi(2S) \rightarrow \gamma\chi_{c2}$  (the horizontal dash-dotted line and the horizontal dotted lines within 6 MeV of it). Thus,  $\pi^0$  candidates were required to have  $|\cos\alpha| < 0.5$ . A preliminary mass spectrum is shown in Fig. 6.

The fit in Fig. 6 is performed with  $M(h_c)$  fixed to its world average [1]. The branching fraction is found to be  $\mathcal{B}[\psi(2S) \rightarrow \pi^0 h_c] = (9.0 \pm 1.5 \pm 1.2) \times 10^{-4}$ , based on  $(25.89 \pm 0.52)$  million  $\psi(2S)$  decays. This is to be compared with the BESIII value [13] of  $(8.4 \pm 1.3 \pm 1.0) \times 10^{-4}$  with 106 million  $\psi(2S)$  decays.

## 7 $\Upsilon(3S) \rightarrow \pi^0 h_b$ search

A selection of events with a maximum value of  $|\cos\alpha| < 0.7$  was found to smooth the background due to  $\Upsilon(3S) \rightarrow \gamma\chi_{bJ}(1P)$  sufficiently (see the left-hand panel of Fig. 7) so that the tightest possible upper limit could be placed on  $\mathcal{B}[\Upsilon(3S) \rightarrow \pi^0 h_b]$ . Choosing the mass range  $9895 \text{ MeV}/c^2 \leq M(h_b) \leq 9905 \text{ MeV}/c^2$ , an upper limit  $\mathcal{B}[\Upsilon(3S) \rightarrow \pi^0 h_b] < 1.2 \times 10^{-3}$  at 90% c.l. was placed [12] (see the right-hand panel of Fig. 7), superseding a previous CLEO 90% c.l. bound [14] of  $2.7 \times 10^{-3}$ .

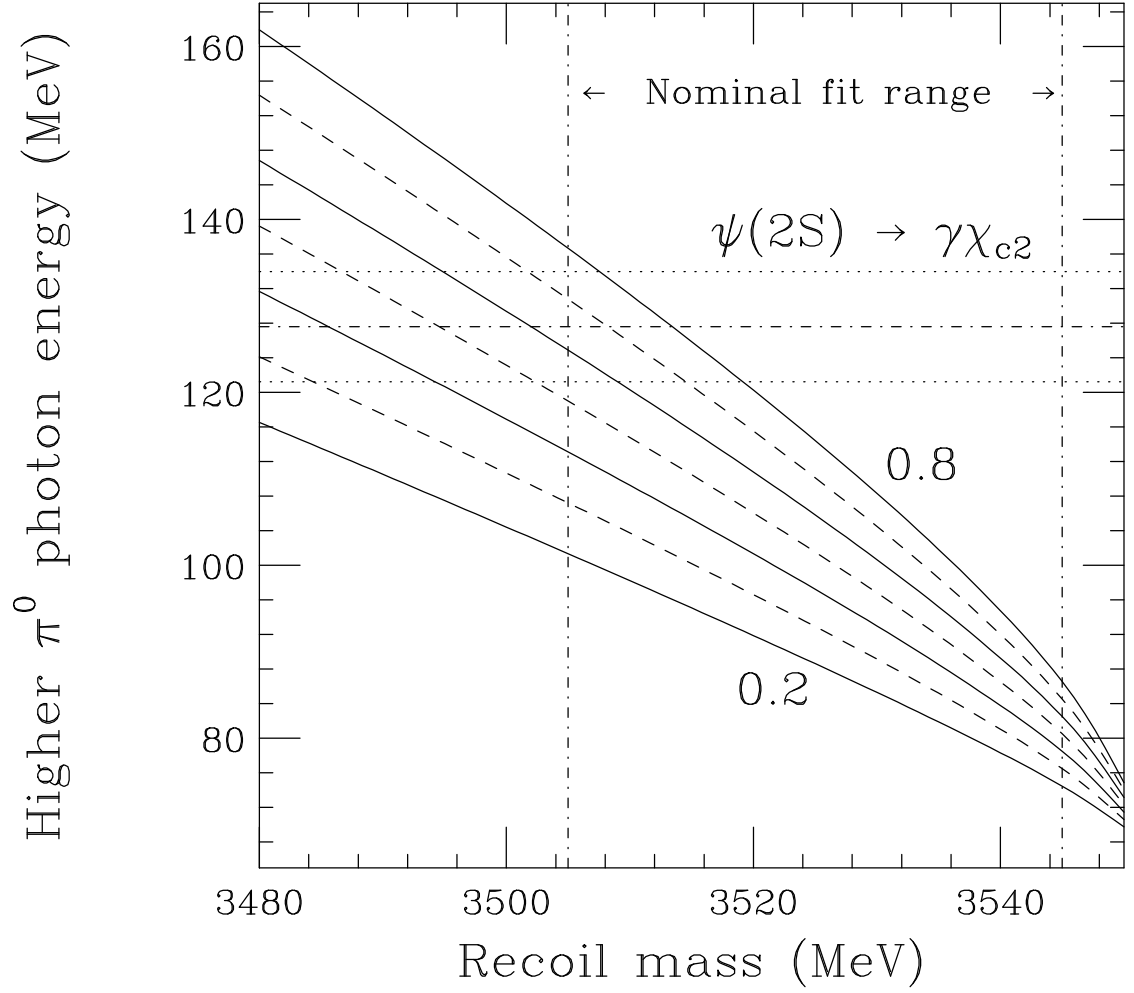


Figure 5: Higher photon energy in  $\pi^0 \rightarrow \gamma\gamma$  vs. recoil mass  $M(X)$  in  $\psi(2S) \rightarrow \pi^0 X$ , for various values of  $|\cos \alpha|$ , where  $\alpha$  is the  $\pi^0$  decay angle (see text).



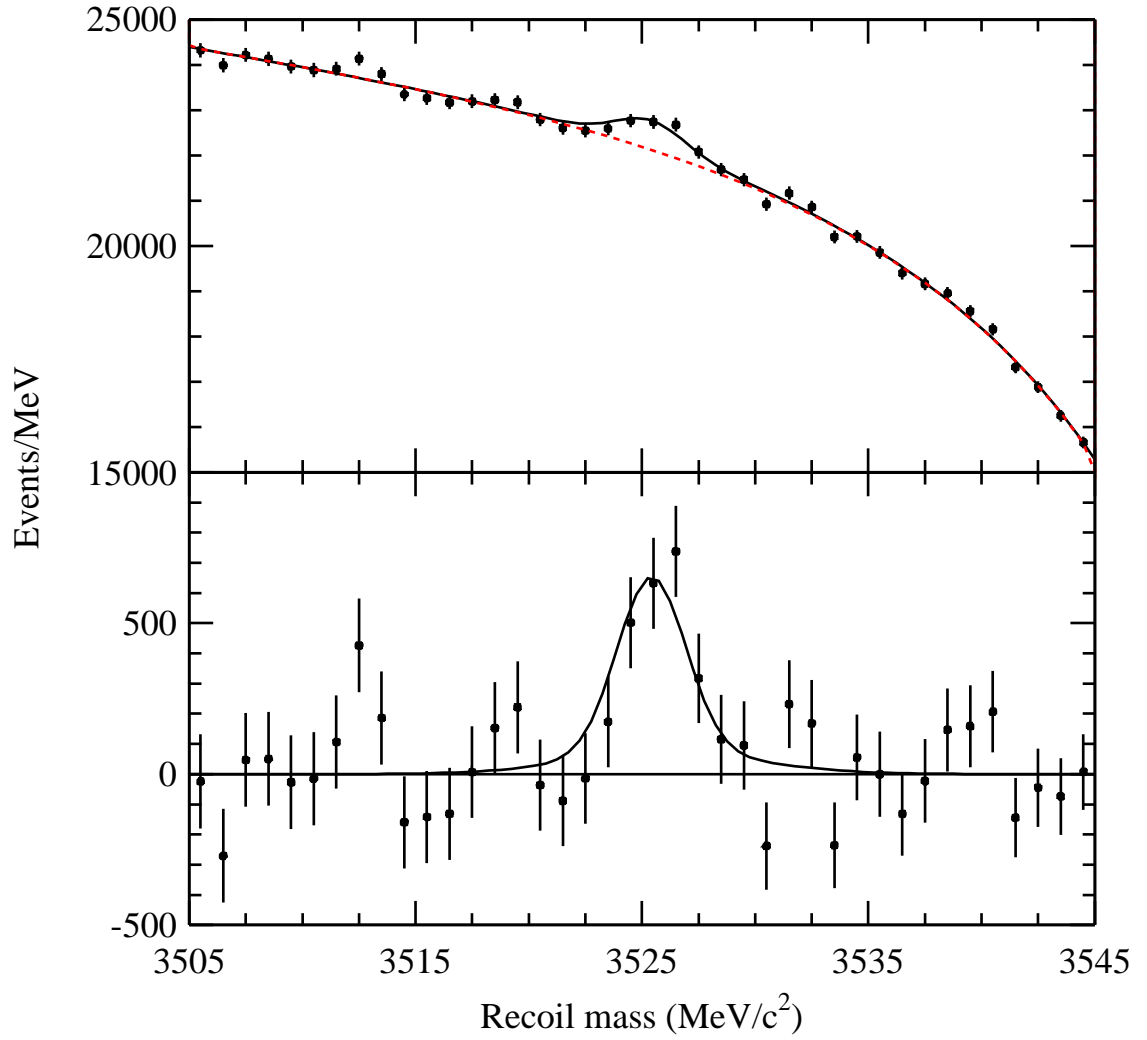


Figure 6: Recoil mass spectrum  $M(X)$  in  $\psi(2S) \rightarrow \pi^0 X$  with the restriction  $|\cos \alpha| \leq 0.5$ . Top: unsubtracted; bottom: background-subtracted.

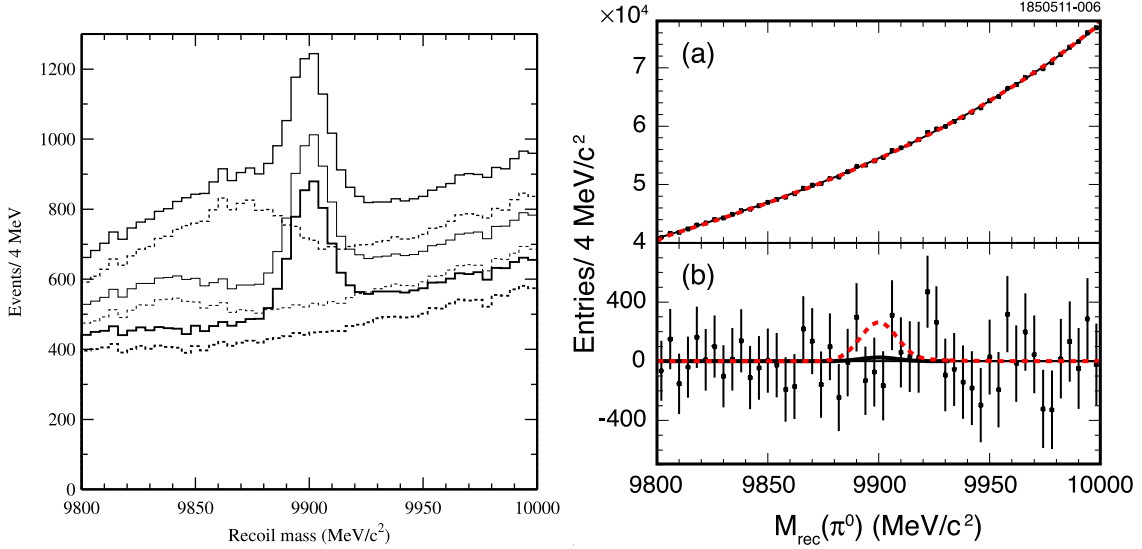


Figure 7: Left: Solid curves show Monte Carlo for  $\Upsilon(3S) \rightarrow \gamma\chi_{bJ}(1P)$  and  $\Upsilon(3S) \rightarrow \pi^0 h_b$  signal Monte Carlo for, top to bottom,  $|\cos\alpha| < 1.0, 0.8$ , and  $0.7$ . Dashes denote corresponding curves for  $\chi_{bJ}$  Monte Carlo alone. Right: (a) Fit to mass recoiling against a  $\pi^0$  for  $\Upsilon(3S) \rightarrow \pi^0 h_b$  with  $M(h_b)$  fixed at  $9900 \text{ MeV}/c^2$ . (b) Fitted background-subtracted spectrum (solid curve). The dashed curve corresponds to the upper limit on signal candidates at 90% c.l.

## 8 Observation of $e^+e^- \rightarrow \pi^+\pi^-h_c$ at $\sqrt{s} = 4170 \text{ MeV}$

BaBar [15, 16] and Belle [17] have observed  $\pi^+\pi^-$  and  $\eta$  transitions from  $\Upsilon(4S)$  to lower states; Belle [18] saw  $\pi^+\pi^-$  transitions from  $\Upsilon(5S)$  to lower  $\Upsilon$  states with rates more than 100 times the  $nS$  rates for  $n \leq 4$  [19]. This led to the question of whether any hadronic transitions could be seen to  $c\bar{c}$  states below flavor threshold from those above it.

Having a large sample of  $e^+e^-$  annihilations at the center-of-mass energy of 4170 MeV (the approximate energy of the  $\psi(2^3D_1)$  candidate), CLEO searched for and found the transition  $\psi(4170) \rightarrow \pi^+\pi^-h_c(1P)$  [20], followed by  $h_c(1P) \rightarrow \gamma\eta_c(1S)$  with  $\eta_c(1S)$  decaying in twelve different exclusive modes. The transition rate was normalized by comparing with the known rate [13] for  $\psi(2S) \rightarrow \pi^0 h_c(1P)$ . In Fig. 8 we denote transitions of interest by red arrows. Evidence for the signal is shown in the lower left panel of Fig. 9.

One selects the  $\eta_c$  using the  $\gamma\pi^+\pi^-$  recoil mass and plots the  $\pi^+\pi^-$  recoil mass. Signal is defined by events with kinematic fit  $\chi^2$  per degree of freedom (d.o.f.) less than 5; background is defined by events with fit  $\chi^2/\text{d.o.f.}$  between 10 and 25. The  $h_c$  peak is shown in Fig. 10, on the left for events where  $\eta_c$  decays to all twelve chosen modes and on the right for events in which  $\eta_c$  decays to modes for which its

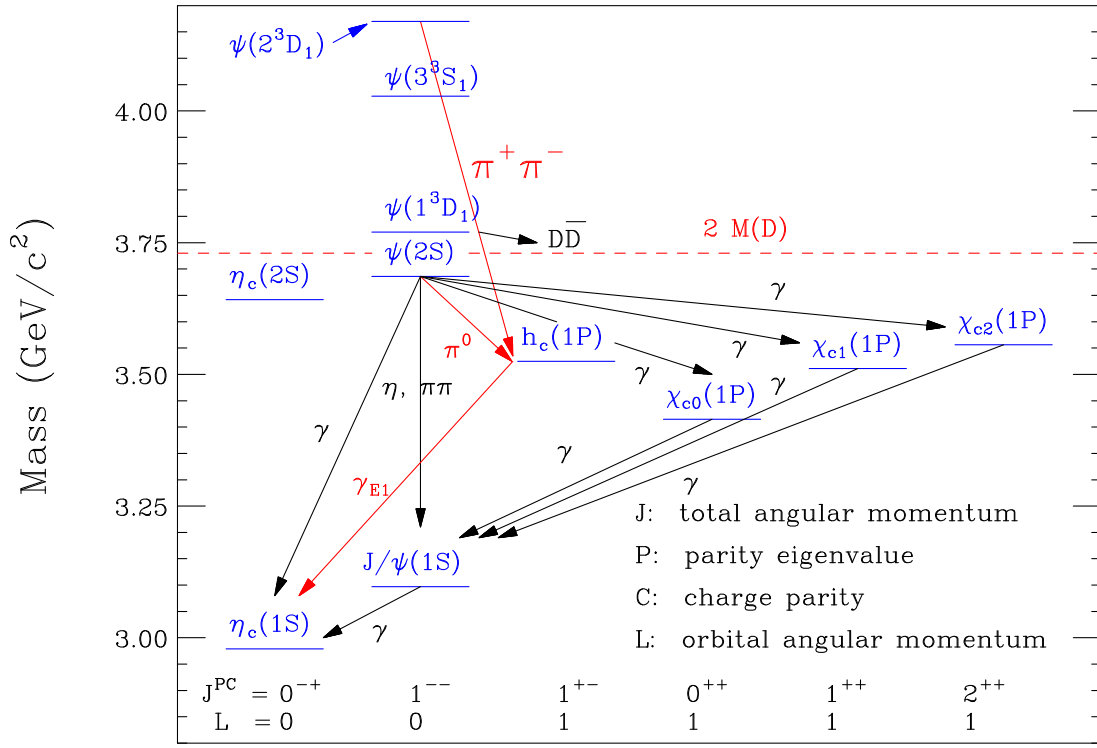


Figure 8: Charmonium spectrum. Red arrows denote transitions of interest:  $\psi(2^3D_1) = \psi(4170) \rightarrow \pi^+\pi^-h_c(1P)$ ,  $\psi(2S) \rightarrow \pi^0h_c(1P)$  (the normalizing transition), and  $h_c(1P) \rightarrow \gamma\eta_c(1S)$  via an electric dipole (E1) transition.

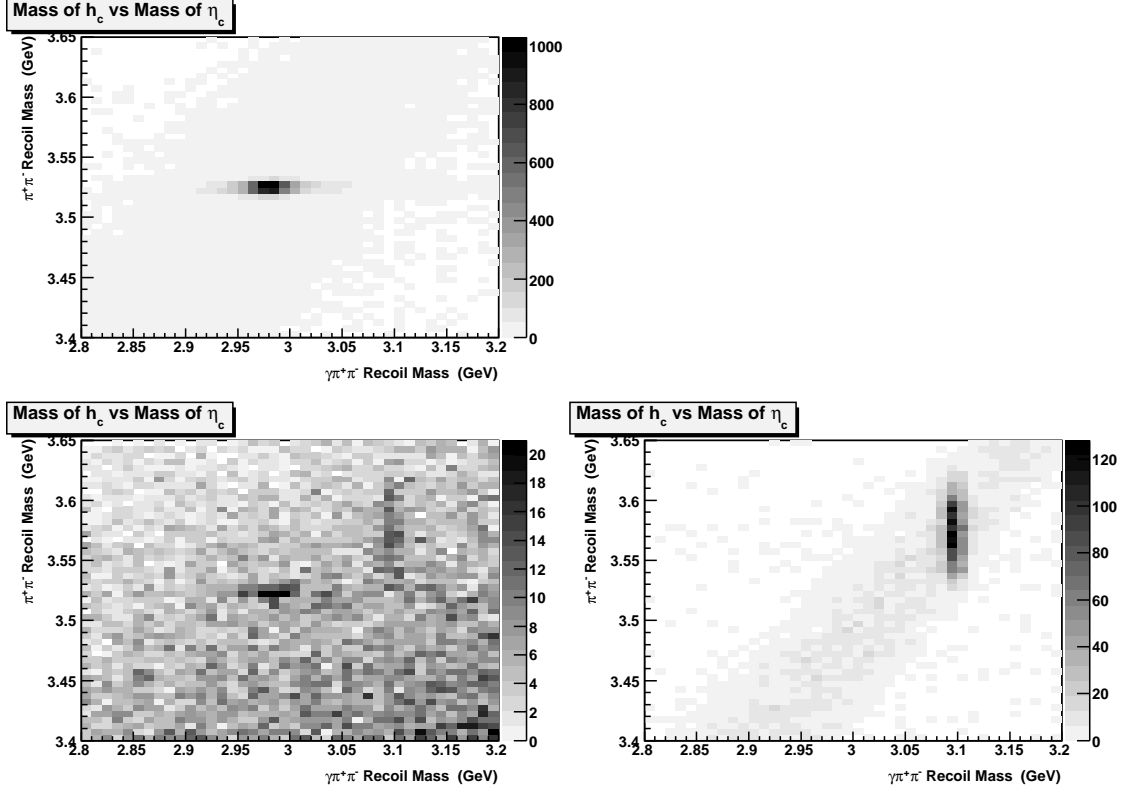


Figure 9:  $\pi^+\pi^-$  recoil mass vs.  $\gamma\pi^+\pi^-$  recoil mass. Upper left: signal Monte Carlo; lower left: data (CLEO); lower right: initial state radiation Monte Carlo. Note that the data shows evidence for both the  $h_c$  signal and the production of  $\psi(2S)\pi^+\pi^-J/\psi$  through the initial-state radiation process  $e^+e^- \rightarrow \gamma\psi(2S)$ .

branching fraction is known. The rate for  $\psi(4170) \rightarrow \pi^+\pi^-h_c$  is found comparable to that for  $\psi(4170) \rightarrow \pi^+\pi^-J/\psi$ , which is curious because the former process involves a charmed-quark spin flip while the latter does not. Signals for  $e^+e^- \rightarrow (\pi^0\pi^0/\pi^0/\eta)h_c$  at 4170 MeV were searched for as well but none found significant.

## 9 $D^+ \rightarrow X\ell\nu$ ; $D_s^* \rightarrow D_s e^+e^-$ ; $D \rightarrow h e e$

CLEO has recently analyzed the decays  $D^+ \rightarrow \{\eta', \eta, \phi\}e^+\nu_e$  [21], finding  $\mathcal{B}(D^+ \rightarrow \eta' e^+\nu_e) = (2.16 \pm 0.53 \pm 0.07) \times 10^{-4}$  (a first measurement) and  $\mathcal{B}(D^+ \rightarrow \eta e^+\nu_e) = (11.4 \pm 0.9 \pm 0.4) \times 10^{-4}$  (a first measurement of the form factor). Comparing the two rates sheds light on the nonstrange quark content of the  $\eta$  and  $\eta'$ . An upper bound  $\mathcal{B}(D^+ \rightarrow \phi e^+\nu_e) < 0.9 \times 10^{-4}$  (90% c.l.) was placed in this same work.

The Dalitz decay  $D_s^{*+} \rightarrow D_s^+ e^+e^-$  has been observed by CLEO for the first time

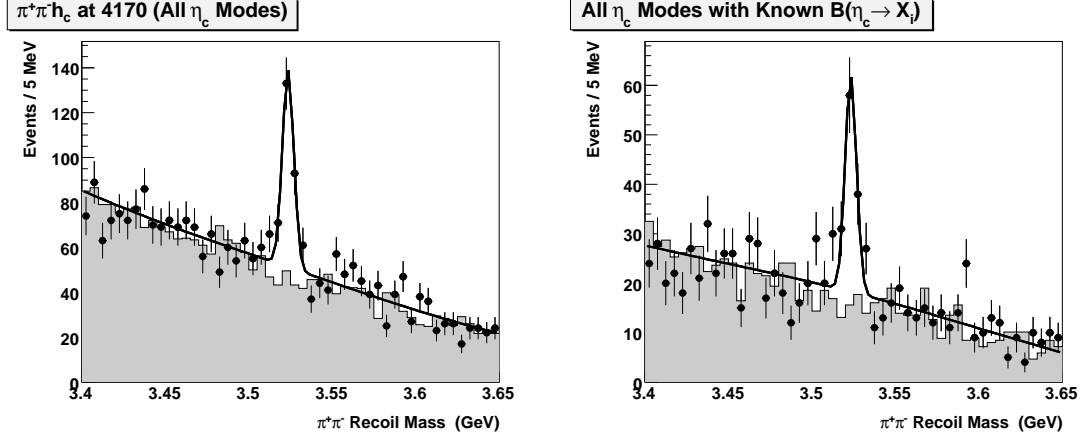


Figure 10: Number of events per 5 MeV vs. mass  $M(X)$  recoiling against  $\pi^+\pi^-$  in  $\psi(4170) \rightarrow \pi^+\pi^-X$ . Left: all  $\eta_c$  modes;  $150 \pm 17$  events with  $9.4\sigma$  significance; right: modes with known  $\mathcal{B}(\eta_c \rightarrow X_i)$ :  $74 \pm 11$  events with  $7.7\sigma$  significance.

Table 3: Summary of CLEO limits [23] on  $D_{(s)} \rightarrow h^\pm ee$  processes.

Decay of:	$D^+$		$D_s^+$	
$ee = h =$	$\pi$	$K$	$\pi$	$K$
$e^+e^-$	$5.9 \times 10^{-6}$	$3.0 \times 10^{-6}$	$2.2 \times 10^{-5}$	$5.2 \times 10^{-5}$
$e^+e^+$	$1.1 \times 10^{-6}$	$3.5 \times 10^{-6}$	$1.8 \times 10^{-5}$	$1.7 \times 10^{-5}$

[22]. The result is  $\mathcal{B}(D_s^{*+} \rightarrow D_s e^+ e^-) / \mathcal{B}(D_s^{*+} \rightarrow D_s \gamma) = (0.72_{-0.13}^{+0.15} \pm 0.10)\%$ , in accord with Standard Model predictions.

Limits have been placed by CLEO on a variety of  $D_{(s)} \rightarrow h^\pm ee$  processes [23]. These are summarized in Table 3.

## 10 $D_s^+ \rightarrow \omega e^+ \nu_e$ bound

$D_s$  Cabibbo-favored semileptonic decays are expected to lead to final states which can couple to  $s\bar{s}$ ; the  $\omega \simeq (u\bar{u} + d\bar{d})/\sqrt{2}$  has none. Hence the decay  $D_s^+ \rightarrow \omega e^+ \nu_3$  tests mixing or a phenomenon known as “weak annihilation” (WA) [24]. One diagram contributing to such a process is shown in the left-hand panel of Fig. 11. A search for this process has been performed by CLEO [25], with the resulting branching fraction  $\mathcal{B}(D_s^+ \rightarrow \omega e^+ \nu_e) < 0.20\%$  at 90% c.l. As shown in the right-hand panel of Fig. 11, one sees evidence for  $D_s^+ \rightarrow \eta e^+ \nu_e$  and  $D_s^+ \rightarrow \phi e^+ \nu_e$  in the three-pion ( $\pi^+\pi^-\pi^0$ ) spectrum  $M_3$ , but not  $D_s^+ \rightarrow \omega e^+ \nu_e$ . In Ref. [24] this branching fraction was estimated to be

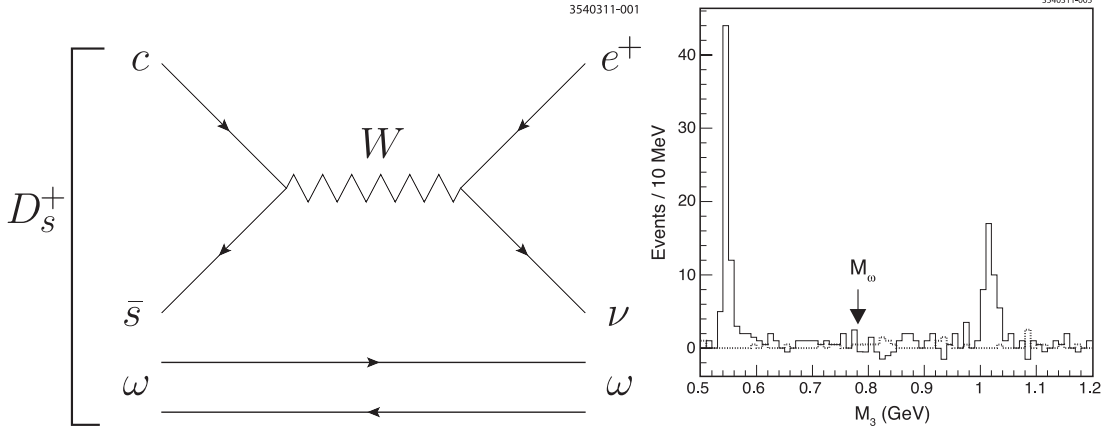


Figure 11: Left: Example of a Feynman diagram contributing to  $D_s^+ \rightarrow \omega e^+ \nu_e$  [25]. Right:  $(\pi^+ \pi^- \pi^0)$  spectrum  $M_3$  in  $D_s^+ \rightarrow \pi^+ \pi^- \pi^0 e^+ \nu_e$  [25].

$(0.13 \pm 0.05)\%$  by assuming  $D_s^+ \rightarrow \omega \pi^+$  is dominated by WA and using factorization, and to be no more than  $2 \times 10^{-4}$  if due to mixing alone.

## 11 Conclusions

CLEO is continuing to contribute to charm (and bottom) physics although it ceased running more than three years ago. Its large sample of correlated  $D$  and  $\bar{D}$  mesons produced at  $\psi(3770)$  can produce information about relative strong phases in Dalitz plots for  $D$  decays, useful in studies of CP-violating  $B$  decays. It has improved knowledge of radiative transitions involving the lowest P-wave  $b\bar{b}$  states and measured some suppressed branching fractions for the first time. The transition  $\psi(4170) \rightarrow \pi^+ \pi^- h_c$ , with  $h_c \rightarrow \gamma \eta_c$ , represents an early observation of a hadronic transition from a quarkonium state above flavor threshold to one below it, possibly indicating the importance of rescattering from flavored meson-antimeson pairs. Numerous  $D$  and  $D_s$  decays (semileptonic, Dalitz, OZI-suppressed) are still being mapped out.

Many questions may require methods beyond the capability of current theoretical approaches. For example, it is easy to pose a problem (“too many quarks”) that lattice QCD can’t handle. We are still learning about  $(c,b)$  mesons after more than thirty years. Many potential tests of our understanding of low-energy strong interactions remain to be performed.

## ACKNOWLEDGEMENTS

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